Vertical off-centering affects organ dose in chest CT: evidence from Monte Carlo simulations in anthropomorphic phantoms

Saltybaeva, Natalia ; Alkadhi, Hatem

Abstract: PURPOSE: The objective of our study was to assess the effect of patient vertical off-centering on organ dose in chest CT with tube current modulation. METHODS: For this purpose, anthropomorphic phantoms representing adult male, female and overweight male were scanned on 192-slice CT scanner at eleven different vertical positions (maximal off-centering ± 5 cm). Monte Carlo simulations were performed for each of the investigated setup, using tube current values extracted from the raw data, in order to obtain 3D dose distributions. Organ doses were calculated as a function of vertical off-centering and compared with the reference values, calculated for the phantoms positioned in the gantry isocenter. Image noise was also calculated as a function of phantoms vertical position using few circular regions of interest. Pearson statistical analysis was used to determine the correlation coefficient between image noise and organ dose values with vertical off-centering. RESULTS: Results of our study showed a significant difference in tube currents applied by the CT scanner when the phantom was scanned in off-centered vertical positions compared to those obtained when the phantom was positioned in the gantry isocenter ($p<0.005$). For all investigated phantom configurations the vertical off-centering below 20 mm in both directions resulted in relative organ dose differences below 7%, while the off-centering above 40 mm was associated with higher organ dose changes of about 20%. The highest relative dose difference of 38% was observed for the thyroid gland at the lowest table positions. A significant correlation between organ doses for breasts, heart, lungs, thyroid and liver and vertical off-centering ($R(2) = 0.909 - 0.998$, $p<0.005$) was found. The relative dose increase associated with lower table position was more pronounced in peripheral organs: breast and thyroid gland. Image noise behaved opposite to the tube current and organ doses and increased at higher table positions. CONCLUSION: Strong vertical off-centering in chest CT with tube current modulation results in misoperation of the TCM function affecting both radiation dose and image noise. Therefore, special attention must be paid to a correct patient positioning in order to optimize organ doses and image quality of the respective CT examination. This article is protected by copyright. All rights reserved.

DOI: https://doi.org/10.1002/mp.12519

Originally published at:
Saltybaeva, Natalia; Alkadhi, Hatem (2017). Vertical off-centering affects organ dose in chest CT: evidence from Monte Carlo simulations in anthropomorphic phantoms. Medical Physics, 44(11):5697-5704.
DOI: https://doi.org/10.1002/mp.12519

Article Type: Research Article

Vertical Off-Centering Affects Organ Dose in Chest CT: Evidence from Monte Carlo Simulations in Anthropomorphic Phantoms

Natalia Saltybaeva, Hatem Alkadhi

Institute of Diagnostic and Interventional Radiology, University Hospital Zurich, University of Zurich, Zurich, Switzerland

Corresponding author: Natalia Saltybaeva

Address: University Hospital Zurich, Raemistr. 100, 8091 Zurich

Tel: +41 (0)44 2558823

E-mail: Natalia.Saltybaeva@usz.ch

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/mp.12519

Abstract

Purpose: The objective of our study was to assess the effect of patient vertical off-centering on organ dose in chest CT with tube current modulation.

Methods: For this purpose, anthropomorphic phantoms representing adult male, female and overweight male were scanned on 192-slice CT scanner at eleven different vertical positions (maximal off-centering ± 5 cm). Monte Carlo simulations were performed for each of the investigated setup, using tube current values extracted from the raw data, in order to obtain 3D dose distributions. Organ doses were calculated as a function of vertical off-centering and compared with the reference values, calculated for the phantoms positioned in the gantry isocenter. Image noise was also calculated as a function of phantoms vertical position using few circular regions of interest. Pearson statistical analysis was used to determine the correlation coefficient between image noise and organ dose values with vertical off-centering.

Results: Results of our study showed a significant difference in tube currents applied by the CT scanner when the phantom was scanned in off-centered vertical positions compared to those obtained when the phantom was positioned in the gantry isocenter ($p<0.005$). For all investigated phantom configurations the vertical off-centering below 20 mm in both directions resulted in relative organ dose differences below 7%, while the off-centering above 40 mm was associated with higher organ dose changes of about 20%. The highest relative dose difference of 38% was observed for the thyroid gland at the lowest table positions. A significant correlation between organ doses for breasts, heart, lungs, thyroid and liver and vertical off-centering (R^2=0.909 – 0.998, $p<0.005$) was found. The relative dose increase associated with lower table position was more pronounced in peripheral organs: breast and thyroid gland. Image noise behaved opposite to the tube current and organ doses and increased at higher table positions.

Conclusion: Strong vertical off-centering in chest CT with tube current modulation results in misoperation of the TCM function affecting both radiation dose and image noise. Therefore, special attention must be paid to a correct patient positioning in order to optimize organ doses and image quality of the respective CT examination.

Key words: CT, organ dose, vertical off-centering, tube current modulation

Introduction

Among the many technological innovations for radiation dose management in computed tomography (CT) imaging, automatic tube current modulation (TCM) is considered one of the most important techniques for optimizing radiation dose while maintaining image quality. [1-3] Several studies reported that usage of TCM results in dose reduction of up to 60% without compromising image quality. [4-6]

The TCM technique is usually based on the width of the patient's body part and its attenuation obtained from the localizer radiograph (LR). Recent studies have suggested that inappropriate patient centering affects both image quality and patient dose when TCM is used. [7, 8] The reason behind this is that inaccurate centering of the patient in the CT gantry results in magnification of the acquired LR if the patient is positioned too close to the x-ray source, leading to overestimation of the patient size and application of higher tube current than is actually necessary. Thus, patient centering is crucial for optimal dose utility when the TCM function is applied. [9]

Several authors have recently addressed this problem and reported that inappropriate patient centering causes misoperation of the automatic TCM system [8] and results in a radiation dose increase of up to 38% compared to the dose values in the gantry isocenter [10, 11]. However, all of these studies estimated radiation exposure in terms of the CT dose index (CTDI). Being one of the key radiation descriptors in CT CTDI is useful for comparing different scanner outputs, however CTDI is independent of the patient size and shape. Moreover, in CT with tube current modulation the CTDI displayed at the end of the scan is averaged over the entire scanned length and does not reflect the changes of exposure associated with TCM. [12, 13] In contrast to CTDI, absorbed dose per organ addresses both the effects of scanner output and the patient characteristics[14], being more relevant for determining potential stochastic risks and deterministic effects from ionizing radiation. [15] The study published in 2013 by Kaasalainen et al. described the effect of patient off-centering on absorbed dose in pediatric CTs. This study investigated the radiation exposure increase associated with misoperation of the bow-tie filter, while the TCM function was switched off. [16] The first study to investigate the impact of vertical off-centering on the absorbed organ dose in CT examinations with TCM was recently published by Kataria et. al. [17] In this work the dose absorbed per organ was estimated as the average reading from a very limited number of point measurements, while more extensive results could be acquired by voxel-based Monte Carlo simulations of organ doses. [16, 17] Therefore, according to our knowledge, no study to date has systematically assessed the effect of patient off-centering on absorbed organ doses in CT examinations with TCM. The purpose of our study was to calculate with Monte Carlo simulations the effect of vertical off-centering on absorbed organ dose from chest CT with TCM using few different CT protocols and three different body type phantoms.

Materials and Methods

Phantom Measurements

An anthropomorphic phantom (CIRS ATOM model 701-B, CIRS, Virginia, USA) representing a standard, adult male (height, 173 cm; body weight, 73 kg) was used. In order to investigate the effect of vertical off-centering on both males and females, the phantom was additionally equipped by custom-made supine breast attachments with a volume of 800 cc for each breast (CIRS, Virginia, USA) representing the realistic anatomy of female breasts when the patient is lying on her back (**Fig. 1a**). In order to mimic an overweight patient, the phantom torso was covered by 5 kg of fat-equivalent tissue (**Fig. 1b**). For all of the configurations (male, female, overweight male) the phantom was positioned on the CT scanner table and was carefully adjusted in the center of the rotating gantry by using two orthogonal LRs as recently proposed. [18]

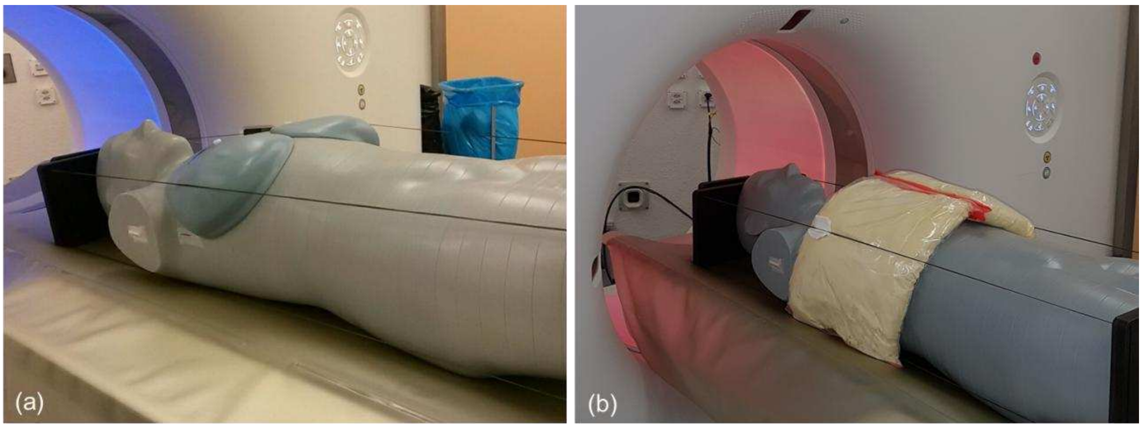

Figure 1. Anthropomorphic female phantom equipped with breast attachments of 800 cc each positioned supine (a) and anthropomorphic overweight male phantom equipped with 5 kg fat-equivalent tissue (b).

All phantoms configurations were scanned with spiral chest protocols on a third generation 192-slice CT scanner (SOMATOM Force, Siemens Healthineers, Germany) with the following parameters: pitch 1, collimation 0.6×96 mm using the z-flying focal spot, gantry rotation time 0.5 seconds, scan length 320 mm. Two different tube voltages of 100 kVp and 120 kVp with quality reference tube current-time products of 100 mAs and 70 mAs, respectively, were applied. Automated TCM (CAREDose4D, Siemens) was switched-on.

In order to investigate the effect of vertical off-centering on TCM and absorbed radiation dose, each phantom was scanned at 11 different vertical positions. The reference position (level: 0) was defined as a table height where the phantoms' antero-posterior midpoint matches the gantry isocenter. Then, vertical positions were varied from 50 mm below to 50 mm above the reference level in 10 mm steps. Prior to each CT scan, a single-projection LR was acquired in order to define individual patient geometry. All LRs were performed with a posteroanterior (PA/bottom) projection at a tube voltage of 80 kVp and a tube current of 20 mA, according to our institutional default protocol.

Radiation Dose

The 3D radiation dose distributions were obtained using Monte Carlo simulations (ImpactMC, CT Imaging GmbH, Erlangen, Germany). [19] The accuracy of the tool was previously validated by measurements in anthropomorphic phantoms on MSCT scanners for different scan protocols. [20, 21] Following interaction mechanisms were considered as the most probable to occur in the energy range used in the study: photoelectric effect, Compton and Rayleigh scattering. If the photoelectric effect occurs, the entire energy of the photon is deposited in the voxel where the event took place and the photon history ends. Secondary particles such as photoelectrons and Auger electrons are not considered since their mean free path length (≈1 mm) is much smaller than the voxel size (1×1×1mm). When Compton or Rayleigh scattering occurs, the new direction of the photon is determined from the differential cross section using the Klein-Nishina formula [22], and the energy of the recoil electron emitted in Compton process is absorbed at the site of the interaction. The sampling process continues until the photon either leaves the volume of interest or its energy drops below 10 keV and the photon is counted as absorbed on the spot. The spectra were generated by the ImpactMC tool according to the publication by Tucker et al. [23] for each of the tube voltages used in the study, anode angle of 7° and taking added and bowtie filtration into account. The information with respect to the shape and material of the filters was provided by the manufacturer. Helical motion of the source was simulated by choosing option "Spiral mode" and providing table increment per rotation calculated as pitch multiplied by the beam collimation. In our study all simulations were performed using the specific scanner geometry, collimation, X-ray spectrum and filtration as used for the CT examinations. Tube angular start and end positions of the exposure together with the individual TCM (a, z) curves were extracted from the raw data by using a manufacturer-provided tool. The CT images of the whole body were acquired for male, female and overweight male phantoms and used as input volume for Monte Carlo simulations. For each voxel contained in the volume the density value was determined from the CT numbers using conversion curves described by Schneider et al. [24] The material in each voxel (air, lung, soft tissue, fat and bone) was established using the threshold-based method by subdividing the CT scale. The actual scan range was also obtained from the raw data in order to take overscanning effects into account. For each dataset 10^9 photon histories were simulated using a graphics processing unit (GPU) cluster. The sampling process continues until the photon either leaves the volume of interest or its energy drops below a certain threshold (e.g., 10 keV).

Based on 3D dose distributions volumes-of-interest (VOIs) for lungs, heart and breasts were overlaid and the organ doses in mGy were calculated as:

$$Organ\ dose = \frac{\sum D_n}{N} \quad (1)$$

where D_n is dose absorbed in voxel defined from MC dose distribution, N– is the total amount of voxels in VOI associated with the organ of interest. The same approach was used to calculate the doses for liver and thyroid in order to evaluate the effect of vertical off-centering on absorbed doses for organs lying outside of the directly examined region. Since the length of the thyroid (~40 mm) is smaller than the beam collimation width used in this study (~57.6mm), the dose to the thyroid may strongly depend on the start angle. Therefore, for each table position the dose to the thyroid was averaged over the phantoms to eliminate the effect of start angle.

The relative difference between organ doses for lungs, heart, breasts and liver from chest CT performed at the different vertical positions were calculated as follows:

$$\Delta D = \frac{[D_i^N - D_0^N]}{D_0^N} \quad (2)$$

,where D_i^N and D_0^N were doses for organ N, calculated for examinations performed at the i-vertical table position and at the reference level 0.

Image Analysis

All CT images were reconstructed with advanced modeled iterative reconstruction technique (ADMIRE, Siemens Healthcare AG, Germany) at a strength level of 3 using a slice thickness of 2 mm, an increment of 1.6 mm, and a medium smooth convolution kernel (Br36). The reconstructed field of view (FoV) was 470 mm and the image matrix was 512×512 pixels.

The image quality was analyzed by measuring the image noise, defined as standard deviation of the HU-values, in various regions of the phantoms:

$$Noise = \sqrt{\frac{\sum_N (x-\bar{x})^2}{N}} \quad (3)$$

,where x - HU value in each pixel, $\bar{x}$ – mean HU and N-number of pixels in the considered regions-of-interest.

Twelve circular regions-of-interest (ROIs) 20 mm in diameter were placed into the lung tissue of the phantoms. In the female phantoms, additional six ROIs were placed in the breast tissue. After calculating the image noise in each ROI as a function of the phantom vertical position, the average noise was compared to the reference noise at a level of 0.

Statistical analysis

All statistical analyses were performed using commercially available software (SPSS, release 22.0; SPSS, Chicago, IL, USA). Student's t-test was used to test whether effective mAs values at each vertical table position were significantly different from corresponding isocenter values. Pearson correlation coefficients (R^2) were used to evaluate the relationship between table position and organ dose values. The same analysis was performed on the relation between the noise and patient off-centering. The confidence levels of 95% were calculated; a two-tailed p-value below 0.05 was considered to indicate statistically significant differences.

Results

Tube current modulation

We found significant differences in TCM values delivered at different vertical positions compared to the reference position (level: 0) for all investigated phantoms and protocols ($p<0.005$). The mean tube current–time products (mAs) delivered by the TCM system at various vertical positions are shown in **Figure 2**. The maximum relative difference in mAs of 27% was observed for the female phantom at the lowest position (level: -5) scanned with 100 kVp, 100 qual. ref. mAs. Since a PA projection LR was used for defining phantom size and attenuation, tube current was largest when the phantom was placed at the lowest table position (level: -5) due to the higher magnification, and lowest when the phantom was placed farther from the x-ray source (level: +5).

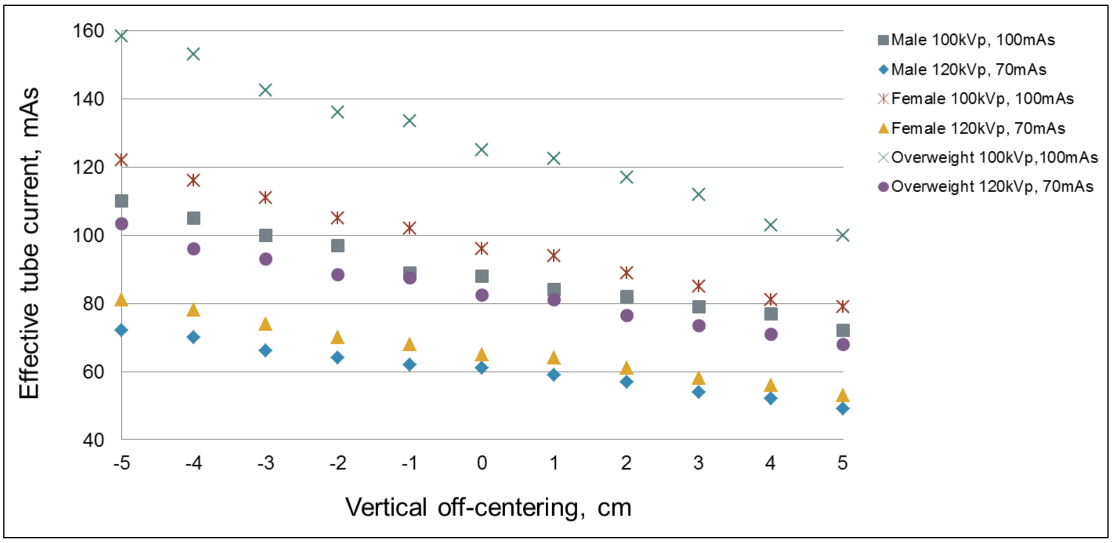

Figure 2. Effective tube current–time product values (mAs) delivered by the TCM system for male, female and overweight male phantoms placed on the CT scanner table at various vertical positions and different protocol settings.

Organ doses

The CT images used as input data for MC simulations and respective dose distributions for the female phantom are shown in **Figure 3.** The organ dose values for the lungs, heart and breasts as a function of vertical off-centering are shown in **Figure 4** for male, female and overweight male phantoms scanned with 100 kVp and 120 kVp, respectively. Similar to the effective tube currents (**Fig. 2**), organ doses for all phantom configurations scanned with 120 kVp were higher than those obtained with the protocol at 100 kVp. A significant correlation was found between organ doses for breasts, heart and lungs and vertical off-centering (R^2=0.94 – 0.99, $p<0.005$). This effect differed among organs, with a less steep regression line for the lungs (slope -0.23) and a steeper regression line for the heart and the breasts (slope values -0.28 and -0.30, respectively, **Fig. 4d**).

Figure 5 shows the absorbed doses for organs outside of the directly examined region: liver and thyroid. The regression lines for the liver are less steep than for lungs (average slope value of -0.17±0.04), while the dose to the thyroid grows up dramatically with the phantom vertical off-centering for both 100 kVp and 120 kVp protocols (slope values -0.67 and -0.83, respectively).

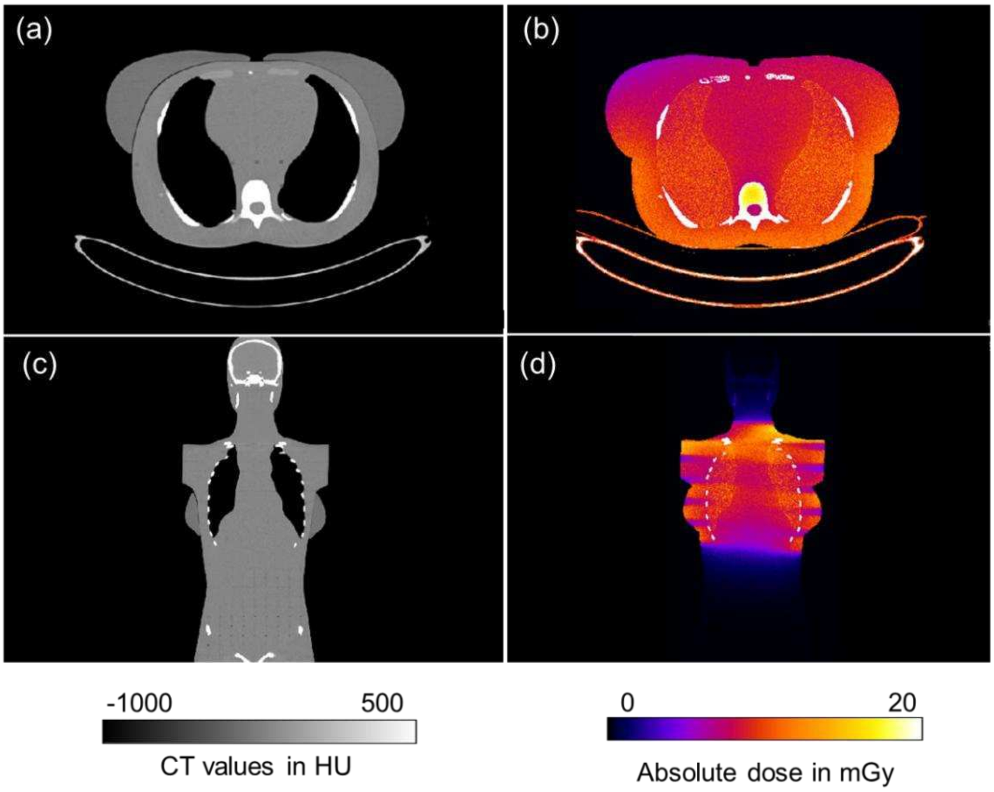

Figure 3. CT images (a and c) and dose distributions (b and d) for the female phantom in the transverse (a and b) and coronal plane (c and d) for the protocol with 100 kVp and 100 qual.ref.mAs.

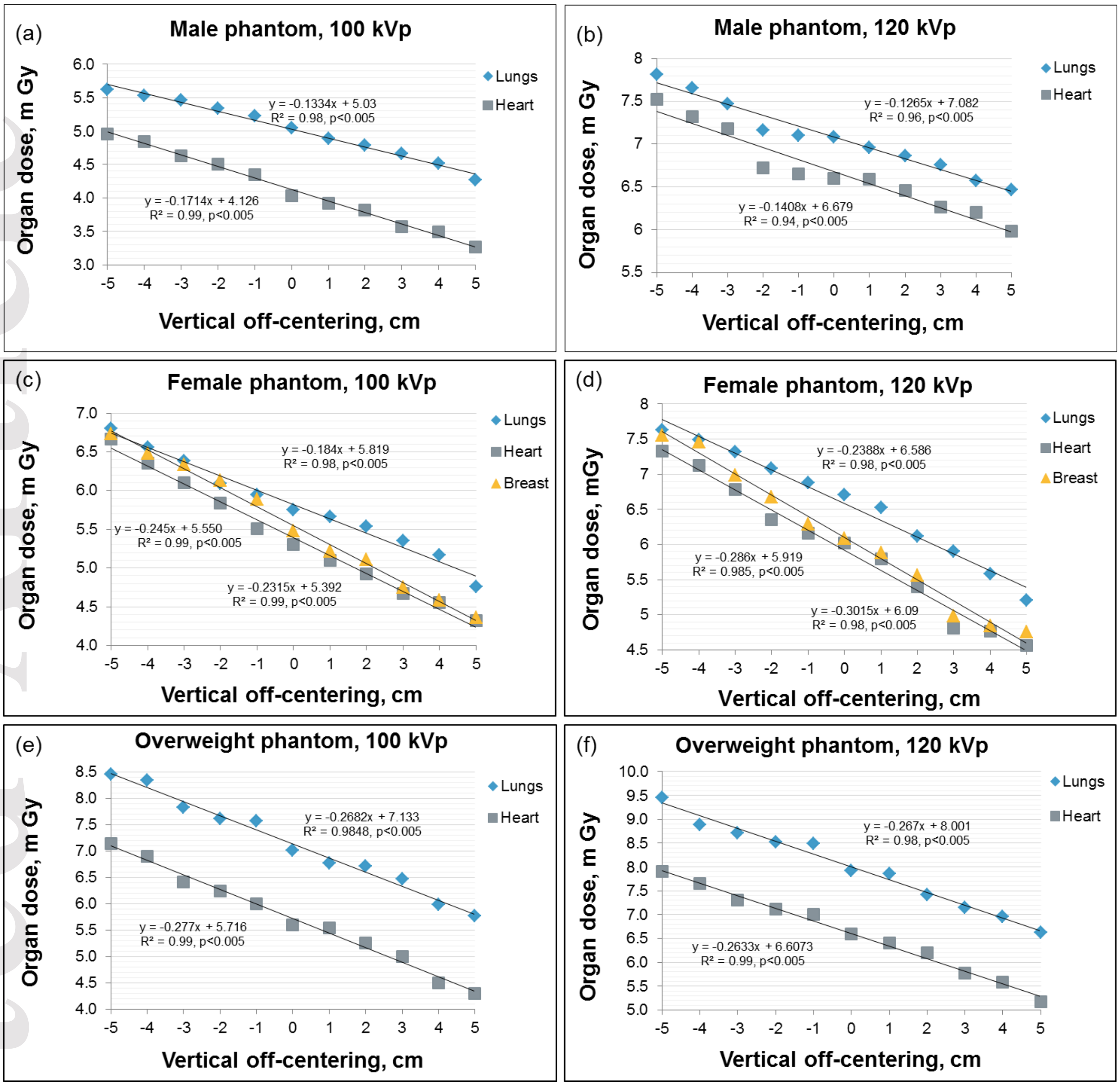

Figure 4. Organ doses as a function of vertical off-centering for (a) the female phantom scanned with 100 kVp, (b) female phantom scanned with 120 kVp, (c) male phantom at 100 kVp, and (d) male phantom at 120 kVp, (e) overweight male phantom at 100 kVp, and (d) overweight male phantom at 120 kVp.

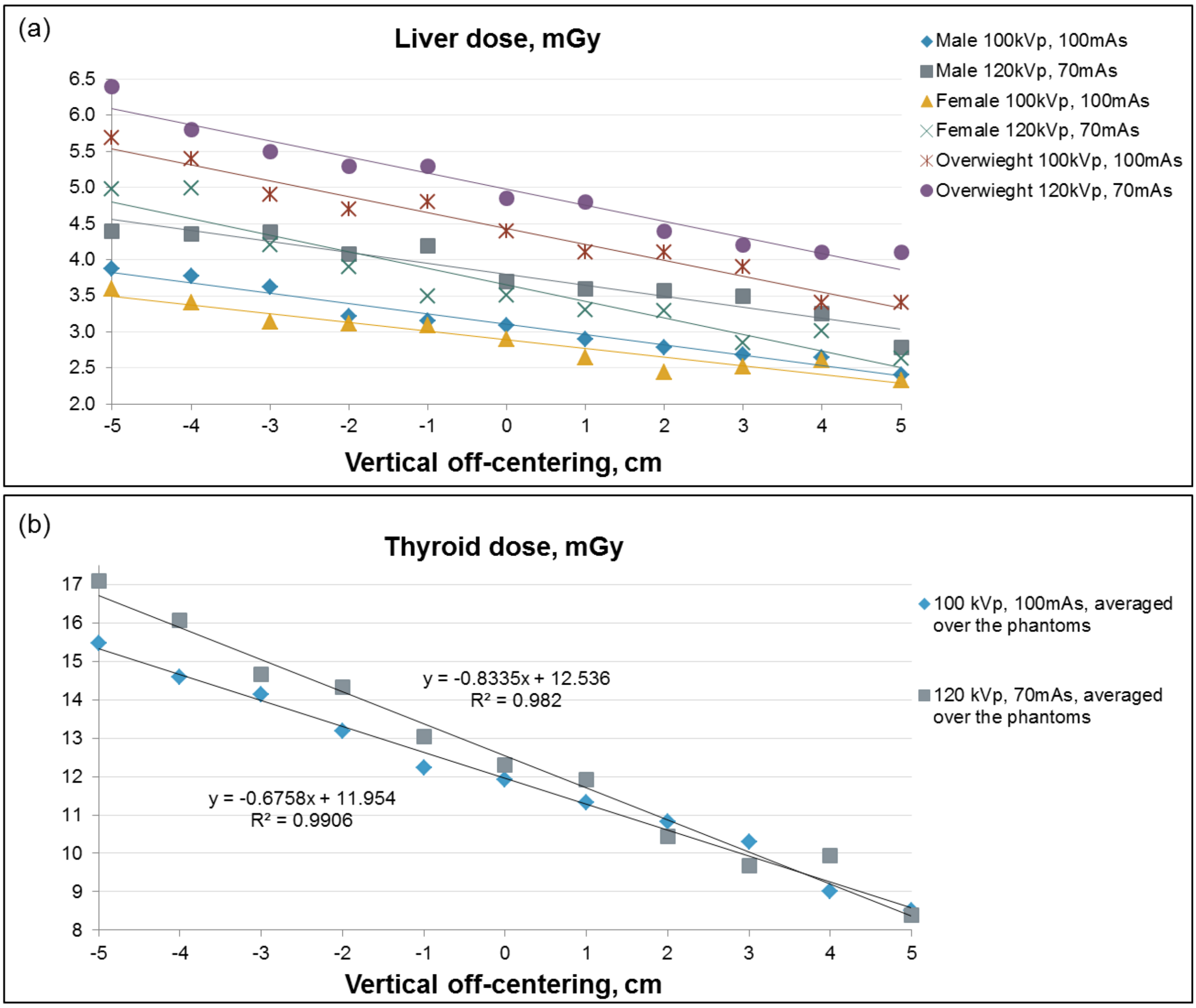

Figure 5. Organ doses for (a) liver and (b) thyroid as a function of vertical off-centering.

Table 1 shows the relative dose differences ΔD for male and female phantoms scanned at 100 kVp and 100 quality reference mAs as a function of vertical off-centering. The highest dose relative difference ΔD of about 38% was observed for the thyroid in overweight phantom at the lower (level: -5) table positions, while the ΔD to the lungs did not exceed 23% for all investigated phantom configurations. Off-centering below 20 mm in either direction resulted in small relative dose differences (average ΔD 7±4%), while off-centering above 40 mm in either direction was associated with higher changes in organ doses (average ΔD 20±7%).

Table 1. The relative dose difference ΔD for lungs, heart, breast, liver and thyroid as a function of vertical off-centering.

Phantom	Off-centering, cm	Organ dose difference, %				
		Lungs	Heart	Breast	Liver	Thyroid
Male	5	-15%	-19%	-	-22%	-31%
	4	-11%	-13%	-	-14%	-30%
	3	-8%	-11%	-	-13%	-6%
	2	-5%	-5%	-	-10%	-3%
	1	-3%	-3%	-	-6%	1%
	0	0%	0%	-	0%	0%
	-1	6%	8%	-	2%	-7%
	-2	11%	12%	-	4%	-3%
	-3	12%	15%	-	18%	10%
	-4	15%	20%	-	22%	6%
	-5	19%	23%	-	25%	19%
Female	5	-18%	-21%	-20%	-20%	-28%
	4	-12%	-17%	-16%	-10%	-11%
	3	-10%	-14%	-13%	-13%	-18%
	2	-7%	-8%	-7%	-16%	-15%
	1	-2%	-4%	-5%	-9%	-7%
	0	0%	0%	0%	0%	0%
	-1	2%	4%	10%	7%	5%
	-2	8%	12%	12%	8%	15%
	-3	12%	15%	16%	8%	25%
	-4	16%	21%	22%	17%	30%
	-5	23%	25%	26%	24%	31%
Overweight	5	-16%	-23%	-	-23%	-27%
	4	-12%	-20%	-	-23%	-32%
	3	-10%	-11%	-	-11%	-16%
	2	-7%	-6%	-	-7%	-10%
	1	-1%	-1%	-	-7%	-9%
	0	0%	0%	-	0%	0%
	-1	7%	7%	-	9%	11%
	-2	7%	11%	-	7%	20%
	-3	10%	14%	-	11%	22%
	-4	12%	23%	-	23%	33%
	-5	19%	25%	-	25%	38%

Image noise

The average noise values as a function of vertical off-centering are shown in **Figure 6** for male, female and overweight male phantoms scanned with 100 kVp and 120 kVp, respectively. The largest relative difference in image noise of 15% compared to the reference value was found for the female phantom scanned with 100 kVp at the highest table position (level: 5). Image noise behaved opposite to the tube current (**Fig. 2**) and organ doses (**Fig. 4** and **Fig. 5**) and increased at higher table positions. In all investigated phantoms configurations, the absolute noise was higher in protocols with a lower tube voltage (100 kVp).

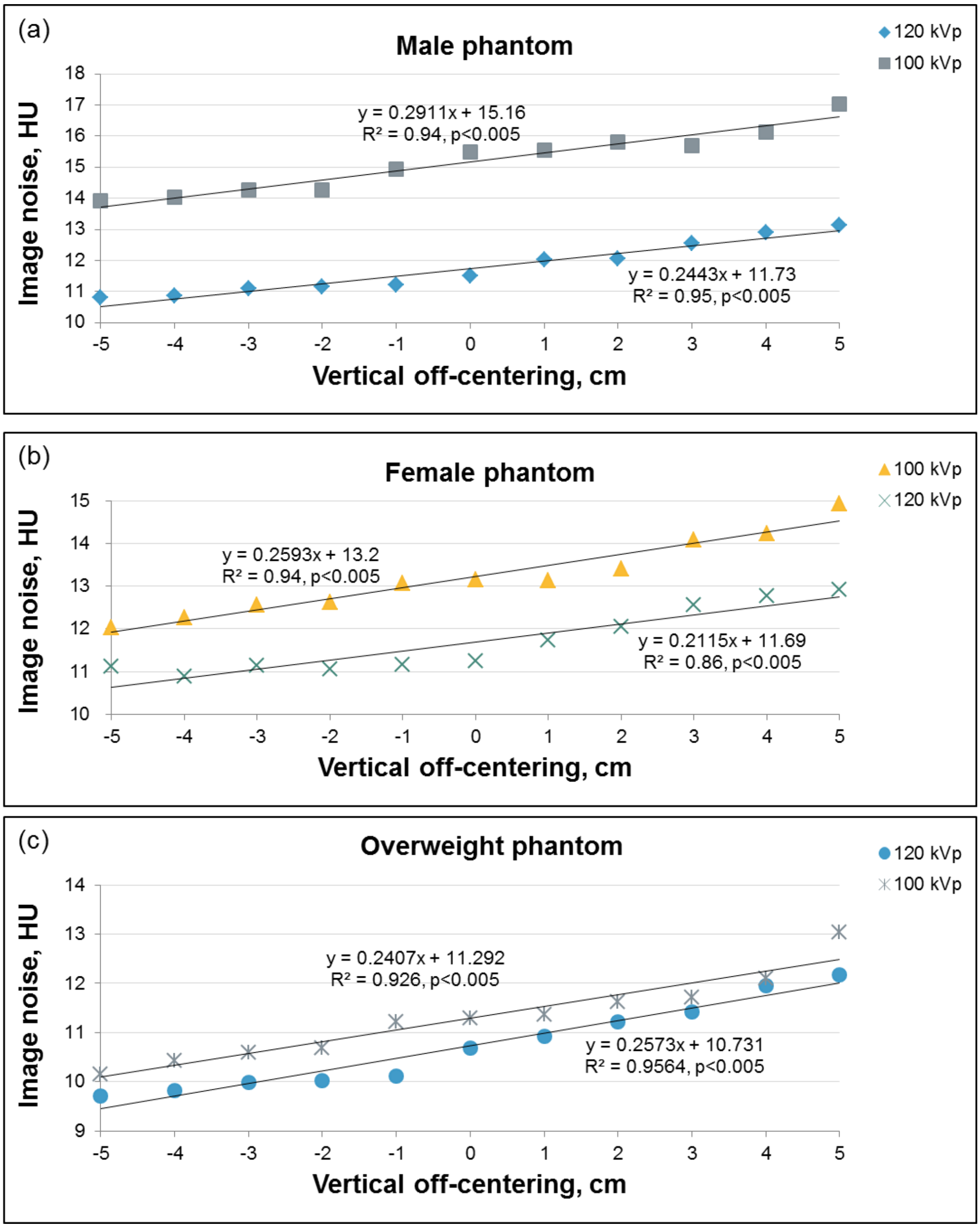

Figure 6. Image noise as a function of vertical off-centering for (a) male, (b) female and (c) overweight male phantoms.

Discussion and conclusion

The automated TCM technique is one of the most important innovations for dose reduction and optimization in CT imaging. With this technique the radiation exposure is adapted according to the size and attenuation of the body region being scanned. Thus, constant CT image quality can be achieved with lower radiation dose. [1, 3, 25, 26] However efficient use of the TCM function requires accurate patient positioning in the gantry isocenter. Our study supports previous observations of Kaasalainen et al.[16] and Filev et al.[11] that vertical patient positioning affects the TCM function and radiation dose. Compared to these studies, we investigated the impact on organ doses, rather than on CTDI values automatically generated by the CT scanner, which is more relevant for determining potential risks from ionizing radiation. [15] Our study systematically investigated the effect of patient vertical off-centering on radiation dose and image quality for several CT scanning protocols, different patient genders and sizes. Additionally, we calculated the dose to the organs lying outside of the directly scanned region.

Results of our study showed a noticeable difference in tube currents applied by the CT scanner when the phantom was scanned in off-centered vertical positions compared to those obtained when the phantom was positioned in the gantry isocenter. This finding reflects basic physical principles, because moving the table towards the x-ray source magnifies the projected area of the subject in the LR, resulting in higher mAs values, and vice versa. In our study the frontal LRs were performed in a PA direction and thus, the highest tube current values were obtained when the phantom was as the lowest position (level: -5). In general, changes in tube current and radiation dose (increasing vs decreasing) depend not only on the direction of vertical off-centering but also on the LR projection.

Organ doses calculated in this study have also shown strong correlation with vertical off-centering. In general, organ doses were higher when the phantom was placed close to the x-ray source (levels: -1, -2, -3, -4, -5) and lower when the phantom was moved in the opposite direction (levels: 1, 2, 3, 4, 5). Interestingly, we observed that absorbed doses of different organs were not changing to the same extent. This can be explained by the fact, that unlike the CTDI values which are increasing proportionally to the effective mAs, organ dose values depend not only on the applied radiation exposure but also on organs position within the x-ray field.

For example, the dose absorbed by the thyroid and the breast in female phantom scanned at 120 kVp placed below the isocenter increased with a higher slope than that of the lungs (slope -0.30, -0.83 and -0.23 for breast, thyroid and lungs, respectively). Such increases in breast and thyroid doses can be explained by the cumulative effect of TCM increase and the additional effect of the bow-tie shape filter. Especially when the phantom is placed at the lowest table position (level -5), the tissues of the breast and thyroid gland are projected to the thinnest and least attenuating part of a bowtie filter during the scan rotation. This effect is less noticeable in lungs and liver, which are larger and more centrally located. Similar effects have been observed by Kaasalainen et al. in their work investigating the effect of bow-tie shape filter on organ dose in patient scanned at different table positions. [16]

The results of our study have shown that the relative organ dose differences for overweight phantom are higher than those for a standard male. This can be explained by the higher magnification of the overweight phantom during LR and thus, higher mAs values applied by the CT system. However, when the kVp is also adjusted to the patient size the overweight and obese patients are scanned at a higher tube voltage and the influence of the tube current is less pronounced. Moreover, it should be mentioned, that according to the studies performed on patients the errors in vertical position are prevalent for thin and small patients than for obese. [9, 27]

Our results have also shown that vertical off-centering below 20 mm results in organ dose differences of around 7%. In contrast, off-centering above 40 mm was associated with significant dose differences of 20% or more. Therefore, special attention must be paid by the CT operator in order to avoid strong patient off-centering.

Vertical patient centering affects not only radiation doses, but also image noise. A strong correlation between image noise and vertical table position was shown in this study. Interestingly, relative changes in image noise were more moderate than those of the dose. For example, positioning the male phantom 5 cm below the isocenter led to a relative lungs dose increase of 16%, while image noise was reduced by only 9%. This can be explained by the fact that radiation dose decreases linearly with tube current, while noise is inversely proportional to its square root.

Our study has some limitations. First, we have only investigated one specific type of CT scanner from a single vendor. Since TCM techniques are proprietary and unique to the different vendors, evaluation of one system's characteristics cannot be extrapolated to other scanners. Second, the phantoms were positioned with the axial center of the phantom in the gantry isocenter based on the two orthogonal LRs. However, the center of attenuation depends on the z-location and therefore does not coincide with the isocenter for the entire scan range, which makes ideal patient positioning a challenging task. [7, 10] Finally, instead of using real female and overweight phantoms, we added bolus material to the standard anthropomorphic male phantom, while the rest of its habitus remaining unchanged.

In conclusion, vertical off-centering of the scanner table in chest CT with TCM results in misoperation of the TCM function affecting both radiation dose and image noise. Therefore, special attention must be paid to a correct patient centering in order to optimize organ doses and image quality of the respective CT examination.

Disclosure

The authors declare that they do not have any conflict of interest.

References

1. C.H. McCollough, A.N. Primak, N. Braun, J. Kofler, L. Yu, J. Christner, "Strategies for reducing radiation dose in CT," Radiol Clin North Am **47**, 27-40 (2009).
2. M. van Straten, P. Deak, P.C. Shrimpton, W.A. Kalender, "The effect of angular and longitudinal tube current modulations on the estimation of organ and effective doses in x-ray computed tomography," Med Phys **36**, 4881-4889 (2009).
3. A.E. Papadakis, K. Perisinakis, J. Damilakis, "Automatic exposure control in pediatric and adult multidetector CT examinations: a phantom study on dose reduction and image quality," Med Phys **35**, 4567-4576 (2008).
4. W.A. Kalender, S. Buchenau, P. Deak, M. Kellermeier, O. Langner, M. van Straten, S. Vollmar, S. Wilharm, "Technical approaches to the optimisation of CT," Phys Med **24**, 71-79 (2008).
5. T.H. Mulkens, P. Bellinck, M. Baeyaert, D. Ghysen, X. Van Dijck, E. Mussen, C. Venstermans, J.L. Termote, "Use of an automatic exposure control mechanism for dose optimization in multi-detector row CT examinations: clinical evaluation," Radiology **237**, 213-223 (2005).
6. M.K. Kalra, M.M. Maher, T.L. Toth, B. Schmidt, B.L. Westerman, H.T. Morgan, S. Saini, "Techniques and applications of automatic tube current modulation for CT," Radiology **233**, 649-657 (2004).
7. N. Saltybaeva, A. Krauss, H. Alkadhi, "Effect of Localizer Radiography Projection on Organ Dose at Chest CT with Automatic Tube Current Modulation," Radiology, 160384 (2016).
8. K. Matsubara, K. Koshida, K. Ichikawa, M. Suzuki, T. Takata, T. Yamamoto, O. Matsui, "Misoperation of CT automatic tube current modulation systems with inappropriate patient centering: phantom studies," AJR Am J Roentgenol **192**, 862-865 (2009).
9. M.A. Habibzadeh, M.R. Ay, A.R. Asl, H. Ghadiri, H. Zaidi, "Impact of miscentering on patient dose and image noise in x-ray CT imaging: phantom and clinical studies," Phys Med **28**, 191-199 (2012).
10. T. Kaasalainen, K. Palmu, V. Reijonen, M. Kortesniemi, "Effect of patient centering on patient dose and image noise in chest CT," AJR Am J Roentgenol **203**, 123-130 (2014).
11. P.D. Filev, P.K. Mittal, X. Tang, P.A. Duong, X. Wang, W.C. Small, K. Applegate, C.C. Moreno, "Increased Computed Tomography Dose Due to Miscentering With Use of Automated Tube Voltage Selection: Phantom and Patient Study," Curr Probl Diagn Radiol **45**, 265-270 (2016).
12. W.W. Mayo-Smith, A.K. Hara, M. Mahesh, D.V. Sahani, W. Pavlicek, "How I Do It: Managing Radiation Dose in CT," Radiology **273**, 657-672 (2014).
13. C.H. McCollough, S.A. Leng, L.F. Yu, D.D. Cody, J.M. Boone, M.F. McNitt-Gray, "CT Dose Index and Patient Dose: They Are Not the Same Thing," Radiology **259**, 311-316 (2011).
14. E. Samei, X.Y. Tian, W.P. Segars, "Determining organ dose: the holy grail," Pediatr Radiol **44**, 460-467 (2014).
15. C.H. McCollough, S. Leng, L. Yu, D.D. Cody, J.M. Boone, M.F. McNitt-Gray, "CT dose index and patient dose: they are not the same thing," Radiology **259**, 311-316 (2011).
16. T. Kaasalainen, K. Palmu, A. Lampinen, M. Kortesniemi, "Effect of vertical positioning on organ dose, image noise and contrast in pediatric chest CT-phantom study," Pediatr Radiol **43**, 673-684 (2013).
17. B. Kataria, M. Sandborg, J.N. Althen, "Implications of Patient Centring on Organ Dose in Computed Tomography," Radiat Prot Dosim **169**, 130-135 (2016).
18. P.A. Harri, C.C. Moreno, R.C. Nelson, N. Fani, W.C. Small, P.A. Duong, X. Tang, K.E. Applegate, "Variability of MDCT dose due to technologist performance: impact of posteroanterior versus anteroposterior localizer image and table height with use of automated tube current modulation," AJR Am J Roentgenol **203**, 377-386 (2014).

19 P. Deak, M. van Straten, P.C. Shrimpton, M. Zankl, W.A. Kalender, "Validation of a Monte Carlo tool for patient-specific dose simulations in multi-slice computed tomography," Eur Radiol **18**, 759-772 (2008).

20 P. Deak, M. van Straten, P.C. Shrimpton, M. Zankl, W.A. Kalender, "Validation of a Monte Carlo tool for patient-specific dose simulations in multi-slice computed tomography," Eur Radiol **18**, 759-772 (2008).

21 W. Chen, D. Kolditz, M. Beister, R. Bohle, W.A. Kalender, "Fast on-site Monte Carlo tool for dose calculations in CT applications," Medical Physics **39**, 2985-2996 (2012).

22 B. M, *Atomic physics*. (Blackie and Son Ltd, London, 1969).

23 D.M. Tucker, G.T. Barnes, D.P. Chakraborty, "Semiempirical model for generating tungsten target x-ray spectra," Med Phys **18**, 211-218 (1991).

24 U. Schneider, E. Pedroni, A. Lomax, "The calibration of CT Hounsfield units for radiotherapy treatment planning," Phys Med Biol **41**, 111-124 (1996).

25 M. Gies, W.A. Kalender, H. Wolf, C. Suess, "Dose reduction in CT by anatomically adapted tube current modulation. I. Simulation studies," Med Phys **26**, 2235-2247 (1999).

26 X. Tian, X. Li, W.P. Segars, D.P. Frush, E. Samei, "Prospective estimation of organ dose in CT under tube current modulation," Med Phys **42**, 1575-1585 (2015).

27 T. Toth, Z. Ge, M.P. Daly, "The influence of patient centering on CT dose and image noise," Med Phys **34**, 3093-3101 (2007).